PESTICIDES IN THE AQUATIC ENVIRONMENT

Effects on Fish Reproduction with Reference to DDT and the Lake Trout fishery of the Muskoka Lakes, Ontario.

TECHNICAL REPORT 4-74

by
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PREFACE

Despite the considerable efforts expended by government agencies in recent years to identify the nature, origins and effects of major environmental contaminants, little or no information exists on the relative significance of pesticides as compared to other materials with respect to their impact on aquatic life. The situation in the Province of Ontario is typical; more than 10 years of monitoring water, sediments and fish tissues for pesticide residues has produced large quantities of data reflecting the generally widespread distribution of certain persistent compounds in the water environment, while the significance of this information in terms of potential biological effect is largely unknown. Furthermore, the incidence of lethal concentrations of pesticides in water would appear to be very low. Over the past three or four years, staff of the Ontario Ministry of the Environment have investigated approximately 40-50 fish kills per annum of which only about 10% were attributable to agricultural pesticide usage. Most of these cases resulted from accident, misuse or negligence on behalf of persons handling or applying the materials. The records available support the conclusion that the use of pesticides in accordance with approved procedures should not result in acute toxicity to aquatic fauna.

While the existing evidence supports the conclusion that damage to aquatic resources due to pesticides has not been excessive, the scarcity of studies on the chronic effects of low-level exposure provides ample reason for continued concern over pesticide inputs to the water environment. Recent work has demonstrated that some materials will affect reproductive processes at levels significantly below lethal concentrations, and suggests that sensitive organisms may gradually disappear from an aquatic community to be replaced by more resistant, but perhaps less desirable forms. Such changes in community structure may go undetected until public concern over deteriorating fisheries stimulates the detailed enquiries necessary to establish the cause of the problem.

This kind of concern brought about the studies which form the basis of the following report. While the problem described resulted from a non-agricultural use of an insecticide, it serves as an example of the suglethal effects which can occur in aquatic species and which may present the greatest threat to the freshwater environment due to introduction of toxic materials.

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INTRODUCTION

The possibility that DDT might cause reproductive impairment in fish was first investigated by Burdick et al. (1964) who showed that levels in lake trout fry in excess of 2.9 ppm in the ether-extractable fat coincided with increased mortality at the stage of egg-sac absorption. This helped to explain the serious loses of fry experienced by the Lake George Hatchery, New York State, between 1955 and 1958. Since that time, DDT has been implicated in declining populations of land-locked Atlantic Salmon (Anderson and Everhart, 1966; Locke and Harvey, 1972) in the state of Maine, and in mortalities of speckled, rainbow and cutthroat trout fry at the Maligne River Trout Hatchery in Alberta (Cuerrier, Keith and Stone, 1967). Experimental evidence for the deleterious effects of DDT on reproduction in cutthroat trout has been provided by Kleinschmidt, Burton and Sinsheimer (1963) and Allison et al. (1964), by Macek (1968) working with brook trout, and by Burdick et al. (1972) using both brook trout and brown trout. From the results of these studies, it is evident that sustained dietary intake of DDT by adult fish, whether through natural or artificially contaminated foods, may result in heavy mortalities amongst the ensuing fry during the period of yolk-sac absorption. Furthermore, such reproductive impairment may be induced by dietary levels of DDT similar to those encountered in natural diets in lakes where declining fisheries are associated with high incidences of DDT usage in adjacent areas.

Prior to the late fifties, Lakes Muskoka, Rosseau and Joseph in the Precambrian area of south-central Ontario, supported an excellent sport fishery for lake trout (Salvelinus namaycush). By the year 1960 the Ontario Department of Lands and Forests had received a number of complaints from sport fishermen which indicated a decline in angling quality for this species in Lake Muskoka. This was in spite of the fact that natural fish populations had been supported by extensive government plants of four to five inch yearling lake trout up to that time. A netting survey conducted by government personnel in 1960, confirmed suspicions that lake trout were not abundant, and that few if any young of that species were present. It was also apparent from the survey that there had been a dramatic increase in numbers of the American smelt (Osmerus mordax) which were introduced to the Muskoka system in the early fifties. It was speculated that this proliferation of smelts may have been, in part, responsible for the reduction in lake trout numbers. The possibility of damage to the fish population by pesticides had not been considered until 1964 when the findings of Burdick et al. were released. It was then apparent to fisheries personnel in Ontario that there were a number of important similarities between the situation in New York State, and that in the Muskoka Lakes District where DDT had been extensively used since the early forties to control biting flies and to combat outbreaks of the forest tent caterpillar.

This paper provides data on the levels of DDT in both cold and warm water fish species from the Muskoka Lakes, and describes a hatchery study to investigate the relationship between mortalities in fry of lake trout from the same system and the levels of DDT in the parents and their offspring.

THE STUDY AREA

The three Muskoka Lakes - Lake Muskoka, Lake Rosseau and Lake Joseph - are situated in the Canadian Precambrian Shield approximately 150 kilometers north of Lake Ontario and 20 kilometers east of Georgian Bay, Lake Huron. The watershed of 4,610 square kilometers is extensively forested and consists of lakes, outwash sands and outcroppings of igneous metamorphic rock. The use of DDT to control biting flies and sporadic outbreaks of forest tent caterpillars commenced as early as 1940 and continued until 1967 when government action prohibited its use for such purposes. Although no official records are available on the quantities applied to the watershed during this period, one commercial applicator has estimated that over the years 1963 to 1967 his company sprayed 2,000 lbs of 100% DDT over some 10,000 acres of forest in this area.

ANALYTICAL CONSIDERATIONS

Since p,p'DDE and p,p'DDD appear to be the major products of breakdown in the environment, recent analyses of fish tissues include determinations on these two metabolites as well as the isomers p,p'DDT and o,p'DDT. However, some of the earlier data shown in the report were produced by an analytical technique involving the destruction and disappearance of p,p'DDD and o,p'DDT, and the conversion of p,p'DDT to p,p'DDE. As a result many of these early analyses were reported as p,p'DDE. Since the precise quantities of p,p'DDD and o,p'DDT destroyed in this procedure cannot be calculated, and since recent results include levels of both isomers and metabolites, it was decided to alter the latter in order to make them comparable to 1966 and 1967 figures. This was accomplished by subtracting o,p'DDT and p,p'DDD from the total DDT complex for all recent fish and gonad determinations, and expressing the result as p,p'DDE. Thus the values utilized in Table 1 must be regarded as minimal. On the other hand, the results of the fry survival study (Table 3) are expressed as 'total' DDT and include o,p'DDT, p,p'DDT, p,p'DDE and p,p'DDD. Notwithstanding the above factors, it was deemed convenient to use the term DDT throughout the text to reflect a common unit of measurement within the individual studies.

FISH SAMPLING PROGRAMME

Fish analyzed for DDT content were netted during the years 1966 through 1971. The results are shown in Table 1. It is evident that considerable differences in DDT content exist between the 13 species represented. However, closer inspection suggests that several important biological and environmental factors might account for such variations. The most evident relationship is between high DDT levels and those species which frequent the deeper and colder regions of the lakes, and which can thus be separated from those fish inhabiting the shallow, warmer water during the summer months. Within these broad categories, it is further apparent that position in the food chain, longevity, size and fat content are all important factors in determining the degree of DDT accumulation by individual species. Although certain anomalies appear to exist, the situation may be well illustrated by the lake trout at one end of the spectrum and the white sucker at the other. The lake trout frequents cold water, is a renowned predator, may live up to 20 years and has a high (mean of 12.9%) fat content. The white sucker prefers warmer water, is not piscivorous, rarely achieves a lifespan of 10 years and has a relatively low (mean of 1.3%) fat content. It is hardly surprising to find that the mean level for DDT in suckers (0.5 ppm) is one fiftieth of that for lake trout (25 ppm).

A comparison of mean DDT levels in fish from the three lakes would suggest a higher degree of contamination in Lakes Muskoka and Rosseau in contrast to Lake Joseph. In addition, there is some indication that Lake Muskoka fish have higher DDT levels than fish from Lake Rosseau. For example, the mean level for lake trout in Lake Muskoka is 35.1 ppm, while mean values for Lakes Rosseau and Joseph are 23.2 ppm and 17.0 ppm respectively. However, this comparison does not take into account size differences in the fish comprising the three samples. Consequently, an attempt has been made to relate DDT concentration in lake trout muscle to weight of fish for each of the lakes (Figure 1). Reference to the graph shows that three-kilogram fish from Lake Muskoka have approximately 24 ppm DDT in the muscle, while fish of the same weight from Lake Rosseau and Joseph have 23 ppm and 16 ppm respectively. It appears that the true difference between Lake Muskoka and Lake Rosseau lake trout is not as great as the

Table 1: DDT IN MUSKOKA LAKES FISH MUSCLE, EXPRESSED AS ppm DDE, WET WEIGHT, 1966-1971

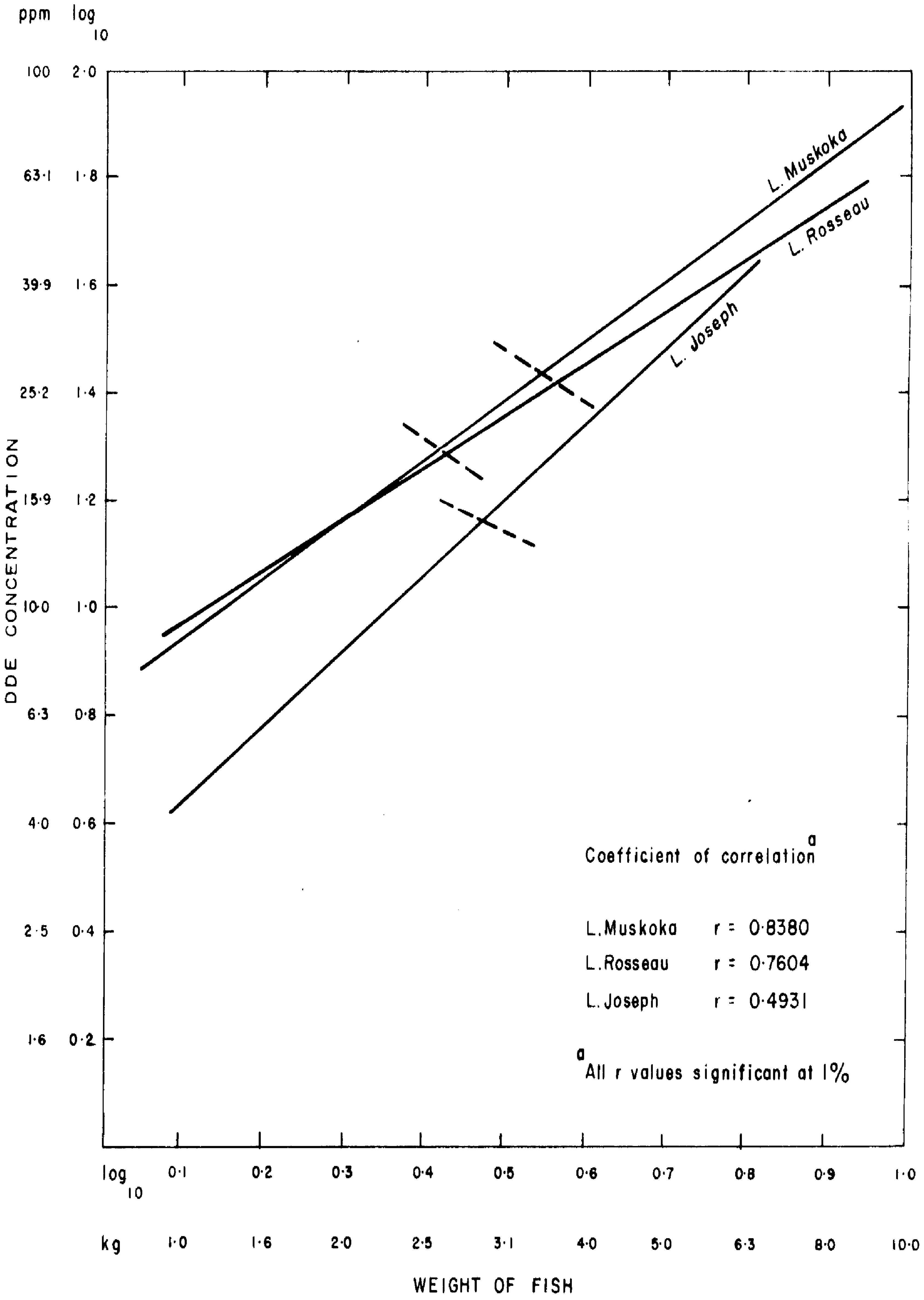
	Range Percent Fat		LAKE MUSKOKA				LAKE ROSSEAU				LAKE JOSEPH			
	Max.	Min.	No. Samples	Max.	Min.	Mean	No. Samples	Max.	Min.	Mean	No. Samples	Max.	Min.	Mean
COLD-WATER SPECIES														
American smelt	12.7	1.1	39	11.4	0.51	1.9	6	3.5	1.0	1.8	8	1.8	0.37	0.94
Burbot	3.5	0.81	3	0.52	0.36	0.44	1	-	-	0.68	1	-	-	0.15
Lake trout	32.3	0.31	66	115.0	1.9	35.1	49	49.4	2.3	23.2	66	49.4	3.0	17.0
Lake trout gonad-male			40	21.4	0.09	4.2	33	91.4	0.34	5.6	31	21.0	0.13	2.5
Lake trout gonad-female			29	44.5	3.6	11.0	20	22.4	1.7	6.4	34	13.6	0.37	4.5
Lake whitefish	11.9	0.58	8	38.5	5.8	20.9	10	22.4	1.6	8.9	7	9.2	0.37	3.9
Shallow-water cisco	17.5	1.4	1	-	-	10.9	7	7.3	1.0	3.1	30	9.7	1.0	3.7

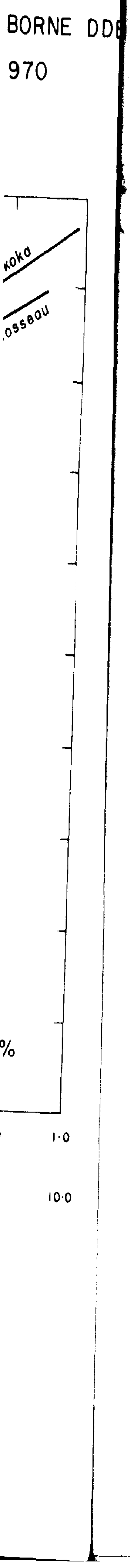
Table 1:(continued) DDT IN MUSKOKA LAKES FISH MUSCLE, EXPRESSED AS ppm DDE, WET WEIGHT, 1966-1971

Table 1: (continued) DDT IN MUSKOKA LAKES FISH MUSCLE, EXPRESSED AS ppm DDE, WET WEIGHT, 1966-1971

	Range Percent Fat		LAKE MUSKOKA				LAKE ROSSEAU				LAKE JOSEPH			
	Max.	Min.	No. Samples	Max.	Min.	Mean	No. Samples	Max.	Min.	Mean	No. Samples	Max.	Min.	Mea
WARM-WATER SPECIES														
Brown bullhead	2.9	1.2	-	-	-	-	2	1.2	0.87	1.0	7	0.84	0.08	0.3
Muskellunge	2.7	1.2	-	-	-	-	3	3.0	1.6	2.1	-	-	-	-
Pumpkinseed sunfish	2.7	2.1	5	0.60	0.14	0.33	-	-	-	-	-	-	-	-
Rock bass	2.8	0.19	15	0.63	0.14	0.32	11	0.39	0.04	0.20	3	0.18	0.04	0.
Smallmouth bass	5.8	0.53	8	6.8	0.13	1.3	10	1.9	0.39	0.92	6	0.58	0.17	0.3
White sucker	2.4	0.36	20	1.6	0.05	0.33	11	0.64	0.07	0.25	17	4.1	0.05	1.
Yellow perch	17.6	0.2	14	1.9	0.10	0.49	4	0.55	0.18	0.35	-	-	-	-
Yellow walleye	5.5	4.5	-	-	-	-	2	13.1	1.9	7.5	3	9.4	4.1	7.

FIGURE:1 PRINCIPAL AXES FOR THE CORRELATIONS OF MUSCLE BORNE DDE WITH WEIGHT OF LAKE TROUT, MUSKOKA LAKES 1966 TO 1970





arithmetic mean would indicate, but that Lake Joseph lake trout are significantly less contaminated with DDT than the former.

A correlation of DDT in lake trout and smelts from nine lakes in the Muskoka area is shown in Figure 2. Data utilized in the graph are tabulated in Table 2. Despite the lack of uniformity of sample size and large weight differences in the fish analysed, a good relationship was found between the DDT contents of the two species. This finding suggests that smelts, a major food item in the lake trout diet, may be an important vector in the transfer of DDT to the latter species.

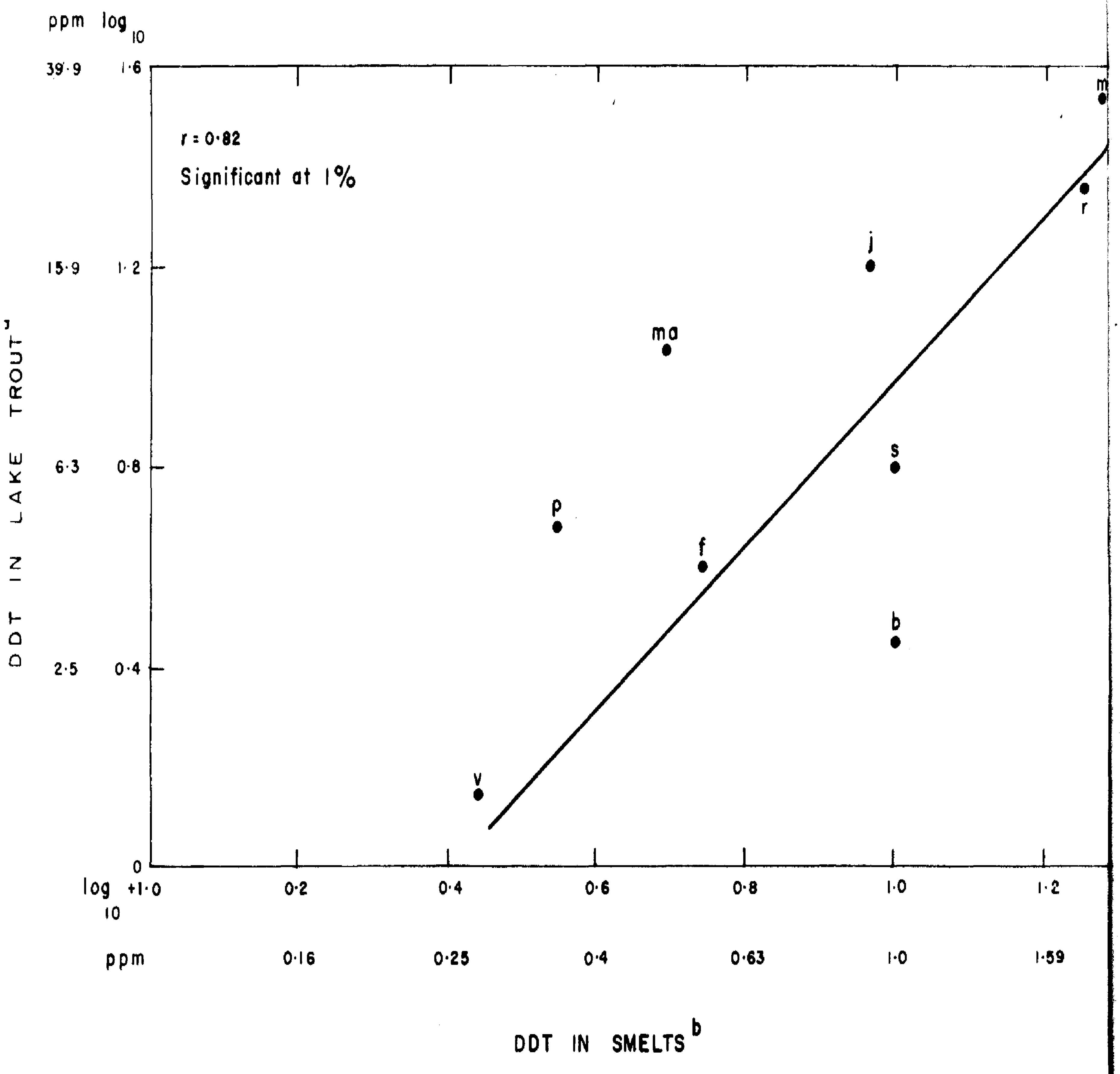
Annual catches of lake trout and other species were not sufficient to precisely define temporal changes in DDT contamination. However, examination of lake trout data obtained yearly from 1966 to 1970 showed no obvious improvements over this period of time. Further collections are planned for the 1974 season to establish the current status of DDT contamination in the lake trout and smelt populations.

LAKE TROUT FRY SURVIVAL STUDY

This study was conducted using eggs from ten large female lake trout taken from Lake Muskoka in November, 1967. Eggs from each female fish were fertilized using male fish from the same source, and each egg lot was incubated separately at the Wiarton Provincial Fish Hatchery. From each parent, samples of muscle and gonad as well as fertilized eggs were submitted for total DDT analysis.

The egg lots were hatched in January, 1968, and in early May, prior to the critical period of yolk-sac absorption, random samples of fry were collected and analyzed for DDT. Throughout the critical period the extent of mortality was recorded and dead fry were reserved for DDT determinations at a later date. In July, samples of the survivors from each egg lot, which were apparently healthy, were submitted along with the dead fry for analysis.Total DDT levels in muscle, gonad and fertilized eggs were determined by the Ontario Water Resources Commission laboratories in Rexdale while fry were analyzed at the Provincial Pesticide Residue Testing Laboratory in Guelph. All analyses were performed by gas chromatography.

FIGURE:2 PRINCIPAL AXIS FOR THE CORRELATION OF MUSCLE-BORN DDT IN LAKE TROUT WITH SMELTS. MUSKOKA LAKES, 1966 — 197



[a] Lake Trout as DDE [b] Smelts as Total DDT.

f: Fairy Lake, j: Lake Joseph, m: Lake Muskoka, b: Lake of Bays, r: Lake Rosseau,

s: Lake Simcoe, ma: Mary Lake, p: Penninsula Lake, v: Vernon Lake.

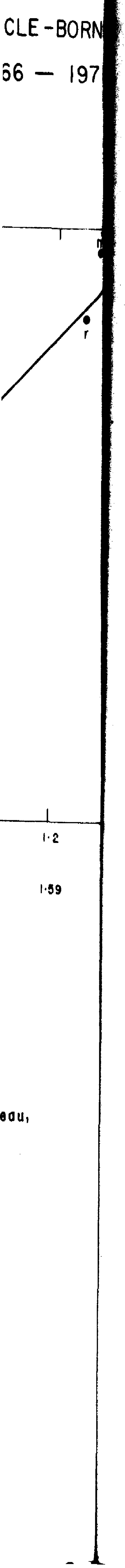


Table 2. MEAN DDT LEVELS IN MUSCLE OF LAKE TROUT AND SMELTS FROM NINE LAKES IN THE MUSKOKA AREA, EXPRESSED AS ppm TOTAL DDT WET WEIGHT

Lake	No. Samples	Lake Trout[a]	Smelts[b]
Fairy Lake	10	4.0	
	7		0.85
Lake Joseph	66	17.0	
	8		0.94
Lake Muskoka	66	35.1	
	39		1.9
Lake of Bays	12	2.8	
	2		1.04
Lake Rosseau	49	23.2	
	6		1.8
Lake Simcoe	5	6.5	
	10		1.1
Mary Lake	10	7.2	
	6		0.50
Penninsula Lake	10	2.9	
	2		0.36
Vernon Lake	10	1.47	
	4		0.28

[a] Lake Trout as DDE

[b] Smelts as total DDT

It must be emphasized at the outset that this study was not designed to simulate the work of Burdick et al. (1964) referred to earlier. In contrast to the latter study which compared fry mortality in lake trout from a large number of lakes, fish were obtained from one lake only and significant mortality occurred amongst all batches of fry (44.6 - 89.8%). Relationships between ranges of total DDT in muscle, gonad, fertilized eggs and fry of 10 fish from Lake Muskoka are portrayed in Figure 3. Total DDT levels are included for fry which died on absorption of the yolk-sac, as well as levels in surviving fry eight weeks later. Complete tabulations of data employed in this summary will be found in Table 3.

Considerable differences were found between DDT concentrations in the muscle (53-128 ppm) and gonad (4.8-15.7 ppm), whereas concentrations in fertilized eggs and fry were not appreciably different to those found in gonad. No relationships could be found between total DDT, its isomers or metabolities and the extent of mortality in individual batches of fry, whether calculated on the basis of fresh tissue or fat content.

In the absence of control data, it is important to ascertain the expected survival of lake trout fry under normal hatchery conditions where interference through DDT contamination is not suspected. Information from local fish hatcheries indicates that some losses (20 - 30%) may be expected at the hatching stage, but that subsequent losses of fry are usually minimal (5 - 10%). This being the case it would appear that losses of lake trout offspring in excess of 40% are infrequent, and that the high mortality of Muskoka Lake fry in the 1968 study must be considered abnormal. The timing and extent of mortality which occurred are characteristic of the 'syndrome' described by Burdick et al. (1964), and although the existence of other detrimental factors such as poor water quality and disease cannot be completely over-ruled, the indications are strong that DDT levels in the fry were responsible for the losses.

Direct comparison between the Muskoka Lakes study and the New York Study is complicated by differences in analytical techniques and the methods used in expressing results. DDT levels in fry of New York lake trout were computed from analyses of egg lots by applying a calculated factor

FIGURE : 3 RANGES OF TOTAL DDT IN MUSCLE, GONAD, EGGS AND FRY OF TEN FEMALE LAKE TROUT FROM LAKE MUSKOKA 1967 AND 1968

FIGURE:3 RANGES OF TOTAL DDT IN MUSCLE, GONAD, EGGS AND FRY OF TEN FEMALE LAKE TROUT FROM LAKE MUSKOKA 1967 AND 1968

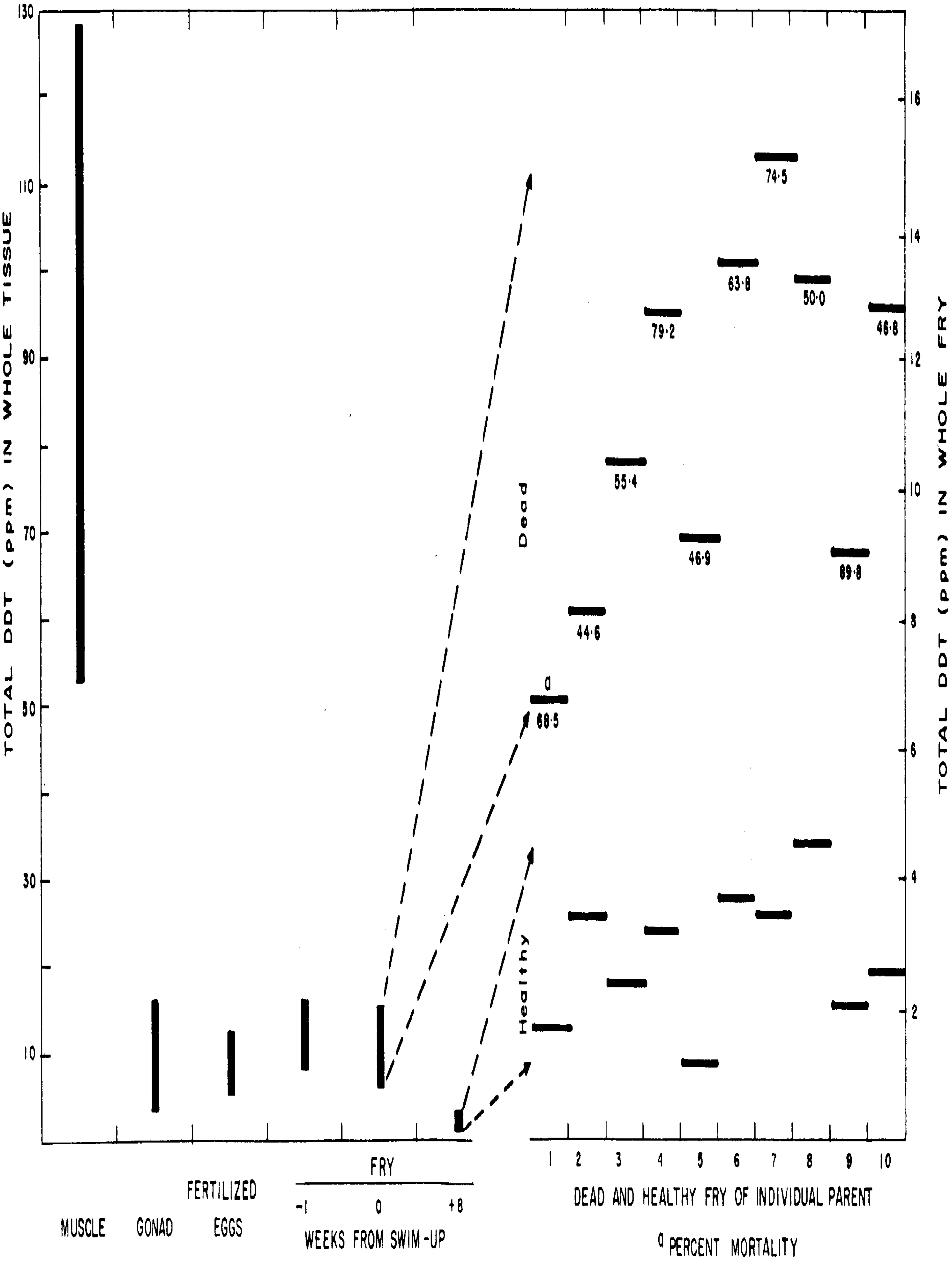


Table 3. LAKE MUSKOKA FRY SURVIVAL STUDY, 1967 - 1968. TOTAL DDT IN INDIVIDUAL PARENTS, EGGS AND FRY AS EXPRESSED AS ppb WET WEIGHT.

Fish No.	Muscle	Gonad	Fertilized Eggs	FRY			
				Immediate Pre Swim-up	Died During Swim-up Period	Eight Week Post Swim-up	Percent Mortality At Swim-up Stage
1	53	4.8	10.6	9.84	6.75	1.65	65.8
2	128	13.5	13.3	12.85	8.16	3.37	44.6
3	62	11.1	13.1	11.48	10.38	2.37	55.4
4	80	8.7	13.3	13.06	12.67	3.24	79.2
5	70	6.9	8.9	13.04	9.20	1.15	46.9
6	76	6.8	10.7	13.72	13.37	3.74	63.8
7	66	7.1	14.2	16.61	15.14	3.50	74.5
8	82	14.8	7.4	10.63	13.26	4.65	50.0
9	53	15.7	11.9	11.29	9.28	2.08	89.8
10	57	5.4	9.6	15.43	12.96	2.57	46.8

for weight increase. Furthermore, the levels reported were for combined DDT and DDD but did not include DDE. On this basis, Burdick et al. estimated the threshold level for appearance of the syndrome (mortality greater than 50%) to be 2.9 ppm. Assuming a valid comparison can be made between Muskoka Lake fry and Burdick's 'computed' fry, the levels for total DDT less DDE in the former exceeded 2.9 ppm in all fry lots.

The similarity betwen lake trout from Lake Muskoka and Lake Rosseau with respect to DDT levels in muscle and gonad would strongly suggest an equally high incidence of reproductive failure in the latter situation. On the other hand the condition in Lake Joseph, where DDT levels were significantly lower, is more difficult to predict. However, data on 5 female lake trout randomly selected from the extensive sampling and with weights falling inside the weight range utilized in the survival study, indicated muscle levels of 18 - 47 ppm and gonad levels of 1.3 - 17 ppm. Since four of the five gonad levels fall within the range of those producing eggs for the survival study (Figure 3), there can be little doubt that some Lake Joseph lake trout were similarly affected.

It would be a great advantage if the quantities of DDT in muscle of adult lake trout could be used to predict the degree of fry survival. The narrow range of DDT levels in gonad, eggs and fry of fish with a wide range of muscle levels, implies that a considerable decrease in adult muscle residues must occur before a significant decrease will be found in the fry. Examination of all data available on female lake trout reveals that gonad levels will not be consistently below 4.8 ppm (lowest level in the 10 survival study fish) until levels in the muscle are approximately 20 ppm or less. It has been estimated that Muskoka Lakes lake trout reach maturity at 6 - 8 years at which time their weights would be in the approximate range of 3.6 - 4.5 kg. Assuming a weight at 7 years of 3.5 kg., from Figure 1 it will be found that the majority of 3.5 kg. fish from Lakes Muskoka, Rosseau and Joseph have muscle levels of about 27 ppm, 26 ppm and 19 ppm respectively. If this line of reasoning is correct, muscle levels in lake trout from Lakes Muskoka and Rosseau must decrease by at least 25% before improvement in reproductive success can be expected. Furthermore, the marginal status of Lake Joseph with respect to successful reproduction is confirmed to some extent. Observations of future trends will help to verify the applicability of this reasoning.

DISCUSSION

The situation described is a classic example of a lake system contaminated by a chlorinated hydrocarbon insecticide contained in run-off and drainage from a shallow-soil, Precambrian area. The persistence of DDT in the deep, cold lake environment, combined with its affinity for organic material and high solubility in animal fats, has lead to bioaccumulation and magnification of the residue levels at the higher levels of the food chain. Analysis of water samples from the Muskoka Lakes has shown a mean value of 0.02 μg/l; by contrast, mean residue levels in warm-water and cold-water fish are greater by factors of 390 x 10^3 and 3,555 x 10^3 respectively.

The Muskoka Lakes problem is an extreme case of pesticide contamination of the water environment. Miles and Harris (1973) and Frank et al. (1974) have compared DDT residues in fish from Ontario waters in both agricultural areas and demonstrate that, despite heavy usage in certain agricultural districts of the southwest, fish contamination is markedly lower than in the Muskoka Lakes system. High loading in run-off from soils with poor retention capabilities, the cold profundal waters providing a slow degradation rate and the existence of large, high fat predators, are the most likely factors in this disparity. Up to the present time, the lake trout population in the Muskoka Lakes is the only one in Ontario in which reproductive failure may be ascribed to high body burdens of DDT. The possibility that other species within the same system may be similarly affected, such as the lake whitefish, has not been investigated.

Recently, the strengthening of legislative controls over the use of persistent pesticides has done much to lessen the chances of recurring problems similar to the one described here. Nevertheless, the experiences with DDT should serve to remind pesticide workers that only the most detailed and thorough toxicological testing of new compounds will serve to ensure protection of exposed populations. Future evaluations of potential effects to aquatic life must emphasize critical stages of development, in particular the reproductive periods. The work of Mount and Stephan (1967) on the butoxyethanol ester of 2,4-D and Carlson (1971) on carbaryl, amongst others, vividly illustrate that reproductive impairment in fish due to pesticide exposures may occur at levels considerably below lethal concentrations. Furthermore, there is a growing feeling amongst aquatic toxicity biologists that some materials may produce deleterious effects on reproduction through short exposures of sensitive life stages such as the eggs and fry of fish (Personal communication, McKim, 1973). This is in contrast to the earlier belief that sub-lethal effects are normally associated with chronic exposures involving both parental and juvenile stages. Should this be so, the possibility of damaging effects from pesticides in streams receiving sporadic inputs may be greater than considered hitherto. As with many environmental contaminants, there is a need for improved criteria for the identification of pest control products and practices with a high potential for aquatic contamination, and for the design of screening methodologies which may be used to establish 'no-effect' levels which extend beyond survival of the individual organism and which will assure the continued welfare of the population and community.

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